# Structure Dynamics, Vortex Dynamics and Fluid Loading for Structures in Waves and Currents

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## LONG-TERM GOALS

The long-term goals of the research are to investigate the dynamics of structures, and their associated wake vortex dynamics, as well as the corresponding fluid loading, when such structures are subject to currents, and to waves. We are investigating the fundamental mechanisms involved in the interaction of current with axisymmetric or cylindrical bodies, including both rigid and flexible structures, which are tethered or free to respond to the fluid forcing. We are studying the in-line and transverse dynamics and forces, wake vortical motions, and signatures of such bodies undergoing vortex-induced vibrations. Our goal is also to investigate the individual and combined effects of orbital motions and amplitude attenuation with depth on the vortex motions and fluid loading on cylindrical structures in waves.

## OBJECTIVES

The objectives of this program remain essentially similar to the previous year, but these have expanded as newer projects have been initiated. The objectives are broadly fourfold.

1. Firstly, we investigate the response and forcing on elastically mounted rigid and flexible bodies (cylinders) in a current, representing one case of a tethered structure in the ocean. We intend to further understand resonance phenomena, and the relation between forcing and wake-vortex dynamics.
2. A second component of the research is the study of the dynamics of tethered bodies (spheres) in currents. Our objective is to investigate further the existence of periodic oscillation modes, the interaction between transverse and in-line vibrations, and the relationship between the dynamics, the forcing and the wake vortical dynamics/signatures.
3. A third component of the program has involved the study of periodic or transient vortex patterns, which can give rise to periodic/intermittent force fluctuations, for vertical and horizontal cylinders in waves.
4. The fourth objective of the research is to understand the vortex-induced vibration of bodies which have a spanwise variation of amplitude, such as for a flexible cylinder, or the simpler case of a pivoted cylinder, both of which examples allow two-degree of freedom dynamics. A related objective is to continue our study of the two degree-of-freedom motions of a rigid cylinder.

## APPROACH

The approach of the research is primarily experimental in nature, but involves analysis, and collaborative computations. We are presently continuing to use our facility, the Cornell-ONR Water Channel, for the primary experiments involving vortex-induced vibrations. We will also be continuing to utilise the computer-controlled X-Y Towing Tank for detailed visualisation and force measurements for bodies in steady/unsteady motion. Use is also made of several of our Wind tunnels to extend some of our tethered bodywork. Techniques have been brought to bear on these problems, including DPIV (Digital-Particle-Image-Velocimetry), Force measurements (using two force balances), and LIF (Laser-Induced-Fluorescence) visualisation.

## WORK COMPLETED

We continue to use and to develop the facilities, techniques, and instrumentation set up in the past years of this effort.

For the components of the research involving Current-Structure interactions, we have further developed the experimental arrangements set up during the course of this research program for the tethered-sphere dynamics problem, and for the cylinder flow-induced vibration problem. Experimental arrangements to allow the dynamics of both flexible cylinders and also pivoted cylinders in a current have been set up. For the tethered sphere vortex-induced vibration study, we use, not only the Cornell-ONR Water Channel, but also a set of wind tunnels, giving us enormous range of parameters - from a mass ratio ($m^*$) of 0.2 in the channel, up to $m^*=940$ in the wind tunnel facilities. For the vortex-induced vibrations of the cylinder, we continue to use the air-bearing ultra-low damping and mass system set up and mentioned in last year's report. For the flexible systems, as well as the two-degree of freedom cylinder set-up, we are using also the water channel.

We have continued to enhance our DPIV system for use in these projects, although our primary interest is in utilising such a system to solve the interesting fluid problems. Our increased image resolution during the last year has been further developed, and we have been able to determine with good accuracy both spatial and temporally resolved turbulence quantities for flows behind vibrating structures. We have been measuring forces, simultaneous with flow visualisations and DPIV measurements for the past five years. Although conceptually difficult, the force-displacement system appears to work very well, and has operated from the outset in 1995 quite effectively.

In our study of the tethered sphere in a current, we have continued to experiment with spherical bodies, of varied mass ratios $M^*$, and varied normalised tether lengths, $L^*$. However, we have also set up the sphere tethered by a tiny rod to the air-bearing system, and measured directly the force and displacement simultaneously, as we achieved for the vortex-induced vibration of the cylinder. The direct measurement of force is compared with indirect calculations of the force, based on the body dynamics. We have been measuring indirectly the forces on the sphere, and have developed a technique to determine such lift and drag directly for this freely vibrating system. Our approach to measuring in-line and transverse displacements of the sphere incorporates the use of advanced technology of image processing, which allows real-time X-Y position information.

## RESULTS

In our most recent experiments concerning vortex-induced vibration of cylinders at extremely low mass and damping, we continue to use a system that has a specific mass of around 1% of that used in the classical work of Feng (1968), which has enabled us to make some fundamental new discoveries concerning vortex-induced vibration.

As mentioned in last year's report, in the case of very low mass-damping, three branches of amplitude are found within the synchronisation regime, as shown in Figure 1, in contrast to the two branches found for high mass-damping in the Feng (1968) classical experiments. As one increases flow velocity, one finds the following branches: the initial excitation regime; the upper branch; and the lower branch.

The vortex dynamics for each of these oscillation modes has now been found from extensive DPIV experiments, and reported in Govardhan & Williamson (*Journal of Fluid Mechanics*, 2000). The initial branch of response is associated with the 2S mode of vortex formation, as defined in Williamson & Roshko (1988), while the Upper branch and the Lower branch are *both* associated with the 2P mode of vortex formation. These modes are clearly shown in the vorticity plots of Figure 2.

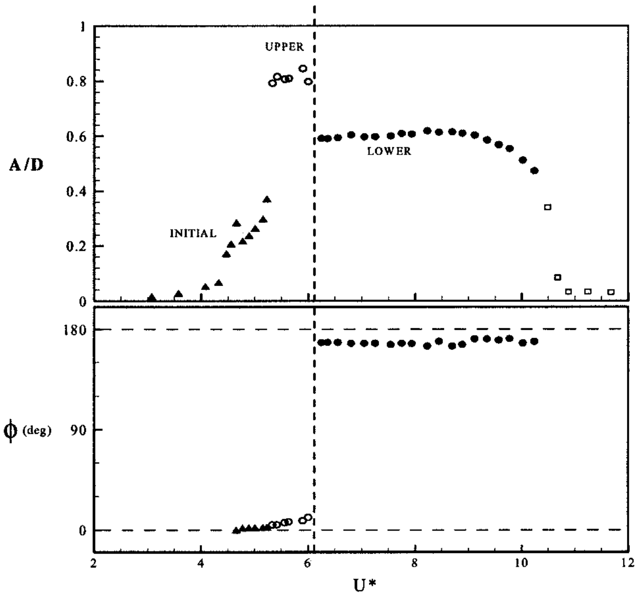


***Figure 1. The three amplitude response branches that are found under conditions of very low mass-damping, namely the initial, upper and lower branches. The jump in phase ϕ (between lift and displacement) occurs between the upper and lower branches.***

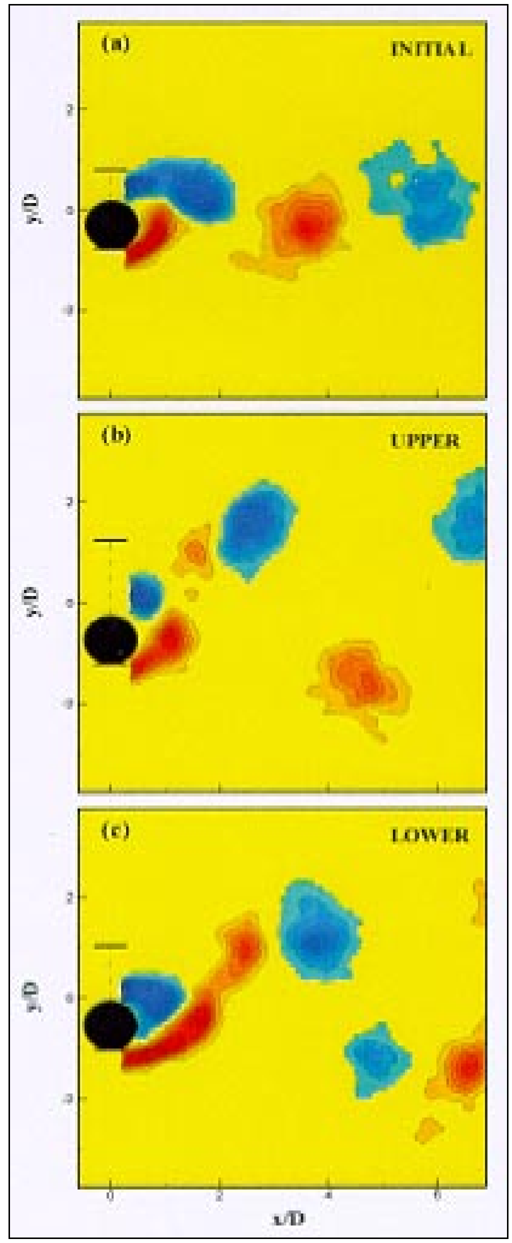


***Figure 2***

In Figure 2, the three response branches are associated with specific vortex modes, as follows: Initial branch - 2S mode; Upper branch - 2P mode; Lower branch - 2P mode. As might be expected, the switch in timing of vortex formation therefore occurs between the Initial and Upper branches.

It is interesting to note that the well-known "jump" in phase ϕ (between lift force and displacement) occurs when the modes change from the upper to lower branch, as seen in Figure 1. One then might expect that the switch in timing of vortex shedding (Zdravkovich, 1982) would occur at the same point. From our DPIV measurements, the switch is evident from a comparison of principal wake vorticity for the different modes, as shown in Figure 3.

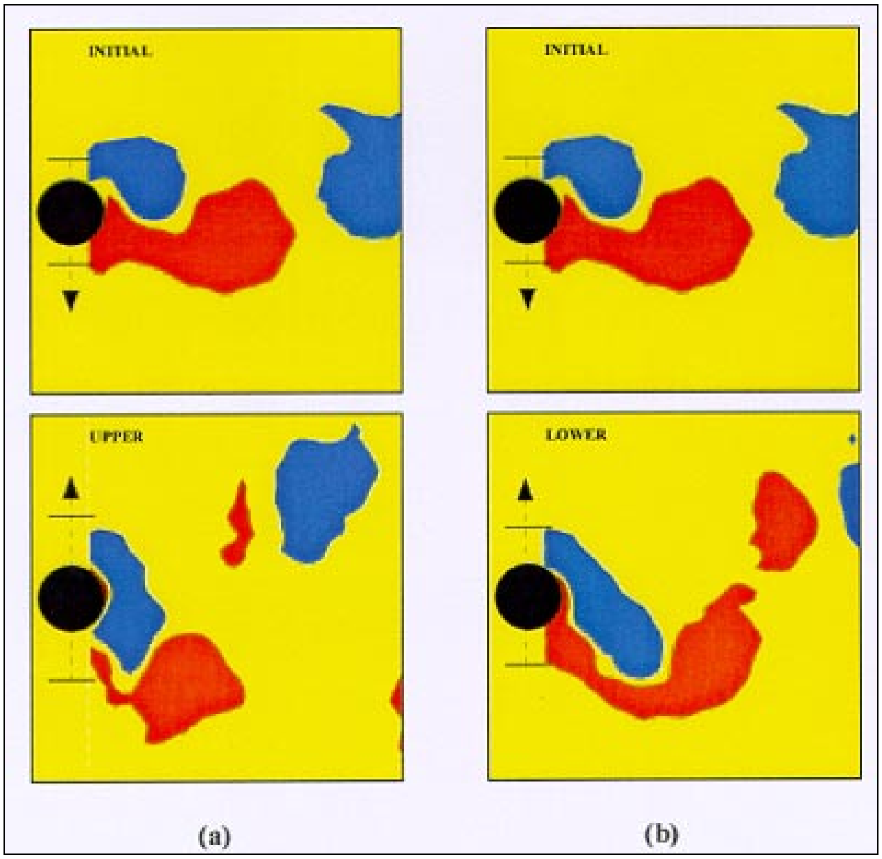


***Figure 3. Switch in timing of vortex shedding between different vortex formation modes. There is a switch of around 180° in the timing between the initial and upper response branches.***

The timing of vortex shedding is similar for the upper and lower branches, yet both modes are about 180° shifted from the initial branch, thus the switch in timing occurs between the initial and upper branches. This switch in timing of vortex shedding clearly does not correspond with the jump in phase $\phi$, in contrast with several previous studies, and in contrast with the original suggestions of Zdravkovich (1982).

On the other hand, at high mass-damping, the "Feng"-type response does indeed exhibit a switch in vortex timing *simultaneously* with a jump in the phase $\phi$, in agreement with the assumptions made in Zdravkovich (1982).

We have further discovered the existence of a CRITICAL MASS for a body undergoing vortex-induced vibration. In the case of the cylinder, the critical mass is given by the mass ratio, $m^*=0.54$. If the mass of the oscillating body falls below this critical value, then the large-amplitude resonant oscillations of the system persist up to infinite flow velocity. In other words, the body never falls out of resonance, no matter how high the free stream velocity is increased. The extent of the synchronisation regime as a function of mass ratio, $m^*$, as measured by a range of normalised velocity ($U^*$) for large amplitude response, is indicated by the shaded region in Figure 4.

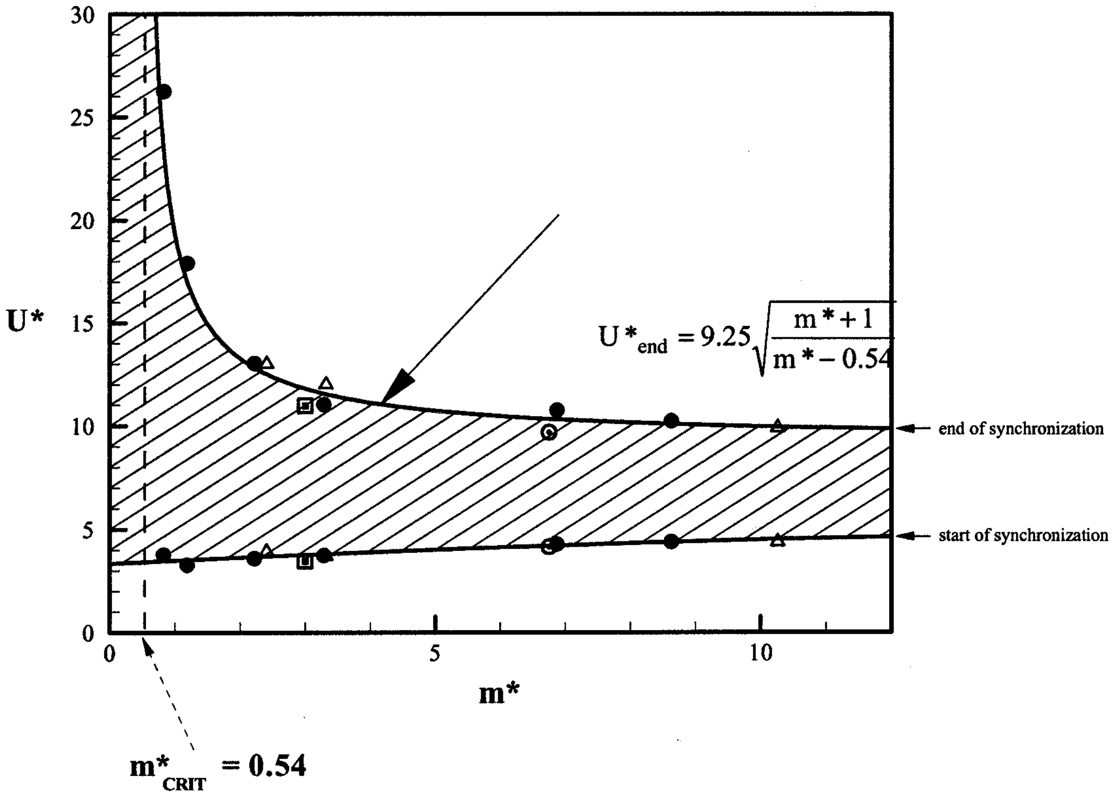


***Figure 4. The extent of the synchronisation regime, as measured by the range of normalised velocity where large amplitude vibrations are found (shaded region), is shown here as a function of the mass ratio, m*. The regime extends to infinity when m* approaches 0.54. Symbols are from our experiments, as well as Khalak & Williamson (1999), Hover et al. (1998), Anand (1985).***

Despite the simple nature of this new and surprising result, it would appear to have significant practical applications. These new discoveries are presented in Govardhan & Williamson (*Journal of Fluid Mechanics*, 2000). It is further found, in a separate study of the dynamics of a tethered or elastically mounted sphere (*Journal of Fluid Mechanics*, 2001), that the critical mass in that case is m*=0.30. In all these cases, we have the surprising result that once the body starts vibrating vigorously, as velocity increases, it never stops! This is very different from the classical view of fluid-structure synchronisation as being restricted to a velocity such that the oscillation frequency is close to the natural structural frequency.

## IMPACT / APPLICATIONS

The investigations described here of current-structure interaction of flexible and rigid cylinders, and of tethered bodies undergoing vortex-induced vibration, have direct application to the dynamics, wakes and surface signatures of tethered or free near-surface bodies. Our investigations of the tethered-body problem show that proper account of the unsteady dynamics of such tethered structures are very important to a correct prediction of the drag and lift force, the tether angles, vortical wakes, and ensuing signatures.

As reported last year, and further studied over the current year, we have investigated systems in both water and air, involving tethered body dynamics, over an enormous range of mass ratios, and having practical application to aero- and hydro-dynamic tethered systems. Synchronised self-excited motions are found to occur over a very large range of normalised velocities, for very low mass ratio, and the frequencies of vibration can depart significantly from the computed still-fluid natural frequency. For high mass ratios, we have discovered 4 distinct modes of large-amplitude vibration, yielding significant response up to at least a normalised velocity of $U^*=300$ (noting that the classical resonance in these systems occurs for $U^*\sim5$). In essence, large-amplitude vibrations can be expected at incident flow velocities very far in excess of the flow speeds predicted from classical synchronisation experiments, and these vibrations are not simply to be found for light structures alone. These results will have an impact on design of tethered and offshore structures.

New discoveries pertaining to the elastically mounted cylinder operating at low mass and damping have been found, which have a practical significance. Our work, published recently in *Journal of Fluid Mechanics*, shows that there exists a critical mass for an oscillating body undergoing vortex-induced vibration. For bodies that are sufficiently light that their critical mass falls below a critical value (depending on the body), the large-amplitude resonant response persists from low velocity up to infinite velocity. Such a "light" body will never fall out of synchronisation, no matter how high the incident flow speed. These distinctly non-classical results have significant practical application.

The fundamental studies of wave-structure interaction will have application to the fluid loading on ocean structures. Our proposed work has led to some understanding of the role of the vortex dynamics on fluid loading for vertical as well as horizontal cylinders in waves.

## TRANSITIONS

It is our intention to verify the present phenomena and data at large-scale, for both the current-structure and wave-structure interactions problems.

## RELATED PROJECTS

Research interactions have been made, and will be made, with several other groups studying vortex-induced vibration and fluid forces in the ocean environment, for example involving visits/seminars (Lehigh, MIT, Oxford, DTU (Denmark), Monash (Australia), IRPHE (Marseille, France), USP (Sao Paulo, Brazil).

The activity in this field has also led to directly relevant conferences (*BBVIV-I* Conference Washington June 1998, which has just been followed by our *IUTAM* Conference on *Bluff Body Wakes and Vortex-Induced Vibration (BBVIV-II)*, Marseille, June 2000. The Principal Investigator is Co-Chairman (with Peter Bearman and Thomas Leweke), where related projects were discussed at length. Collaboration on four of our projects involve personnel, and accepted or submitted publications, at Lehigh University (Don Rockwell), at USP, Brazil (Celso Pesce, Julio Meneghini), at CSIRO, Melbourne, Australia (Hugh Blackburn), and at IRPHE, Marseille, France (Thomas Leweke).

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